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An efficient spatial domain technique for subpixel image registration

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ABSTRACT

In this paper a new technique for performing image registration with subpixel accuracy is presented. The proposed technique, which is based on the maximization of the correlation coefficient function, does not require the reconstruction of the intensity values and provides a closed-form solution to the subpixel translation estimation problem. Moreover, an efficient iterative scheme is proposed, which reduces considerably the overall computational cost of the image registration problem. This scheme properly combined with the proposed similarity measure results in a fast spatial domain technique for subpixel image registration.

1. Introduction

Many image processing applications require an image registration scheme in order to estimate the underlying correspondence between two or more images, which have been acquired either by a single sensor at different times, or by different sensors at the same time but from different viewpoints, or by a combination of the above. Two examples of such applications are remote sensing and biomedical imaging. For remote sensing, registration of infrared to visible spectra is very important for studying satellite images of the earth. Image registration is also very useful for the medical community, since can lead to substantially enhanced diagnosis, in surgical planning, or in the fusion of images coming from different modalities.

Many techniques have been proposed for image registration. Two basic categories are the feature-based and the intensity-based techniques [8,42]. Feature-based techniques first identify edges, contours or other features common to the compared images and then find the mapping between them [22,15,10]. This results in reduced computational complexity. However, the problem of identifying features is rather complicated and these techniques are very sensitive to the accuracy of the feature extraction stage. On the other hand, intensity-based techniques are more computationally demanding, but avoid the difficulties of feature extraction.

Another classification of the existing image registration techniques can be made based on the domain of implementation (frequency or spatial domain). A well-known frequency domain technique is phase correlation [11]. Many other Fourier-based [9,31], as well as wavelet-based [12], techniques have also been proposed in literature. Note that some methods obtain pixel-level registration that may be adequate for some applications. On the other hand, there are applications that require registration with subpixel accuracy.

The most commonly used methods that provide subpixel accuracy are based on interpolation [36]. The phase-correlation interpolation is such an example. In [37], an algorithm for registering multiple frames simultaneously using nonlinear minimization in frequency domain is described, based on the assumption that the original image is bandlimited. In [16], three new algorithms for 2D translation image registration to within

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a fraction of a pixel are presented that use nonlinear optimization and matrix-multiply discrete Fourier transforms. The accuracy of these algorithms is equivalent to that of the conventional fast Fourier transform upsampling approach, while the computational cost is significantly reduced. The authors of [20] propose a frequency domain technique for registration of aliased images. Their technique is based on spectrum cancellation, that is, elimination of the aliased frequency components. Reddy and Chatterji in [31] use the so-called phase correlation of the log-polar transform of the images and apply a high-pass emphasis filter to strengthen high frequencies in the estimation. Another Fourier-based algorithm for image registration with subpixel accuracy is presented in [33], where the pure translation case is investigated. The algorithm detects and removes the frequency components that might cause errors in the shift estimation due to aliasing. In [13], it is shown that the signal power in the phase correlation corresponds to the polyphase transform of a filtered unit impulse centered at the point of registration. Recently, in [38] a frequency domain technique has been proposed for the registration of aliased images, based on their low-frequency, aliasing-free (or marginally affected by aliasing) part. The phase difference between the compared images is computed and for the aliasing-free frequencies the corresponding system of linear equations is formed and the optimal shift parameters result from its least squares solution.

It is easier to describe and handle aliasing in frequency domain, but frequency domain methods are more suitable for global motion models. On the other hand, spatial domain methods generally allow for more general motion models. Some typical criteria for intensity-based registration are the minimization of the squared error between the compared images, the correlation maximization [28] and the maximization of mutual information [40,41,27].

Intensity and correlation interpolation can be used to provide subpixel accuracy [36]. However, the accuracy of these methods depends highly on the interpolation algorithms performance. Other approaches are based on the differential properties of the image sequences [36], or formulate the subpixel registration as an optimization problem [37,20,35]. These approaches rely on the image intensity conservation assumption. In [19], an iterative scheme based on Taylor expansions is presented and a pyramidal scheme is used to increase the precision for large motion parameters. Earlier, Lucas and Kanade in [23] presented an image registration technique that makes use of the spatial intensity gradient of the images to find a good match, using a type of Newton–Raphson iteration. Then, in order to handle large motions, Bougeut implemented a pyramid-based version of the Lucas–Kanade technique [4,5]. The authors of [1] use sparsely sampled regional correlation, providing accuracy better than 0.2 pixels. In [26], an error function linear in the model (local affine) parameters is minimized using least-squares. This error function is then augmented with a nonlinear smoothness constraint, and the least-squares solution is used to bootstrap an iterative nonlinear minimization. This entire procedure is built upon a differential multiscale framework, allowing the capture of both large and small-scale transformations.

The technique proposed here has been motivated by the approach suggested recently in [29], where a correlation-based method for stereo correspondence is presented. The proposed technique aims to maximizing the correlation coefficient, which is a measure that provides robustness to photometric distortions. In contrast to the interpolation-based techniques, the proposed one does not require the reconstruction of the intensity values and provides an easily computed closed-form solution to the subpixel translation estimation problem. Moreover, an efficient iterative scheme is proposed, which reduces considerably the overall computational cost of the image registration problem. This scheme properly combined with the subpixel accuracy technique results in a fast spatial domain technique for subpixel image registration. Note that if exhaustive search is used for the maximization of the correlation coefficient, N^2 searches are required, where N is the number of searches in each dimension. Using the proposed scheme for the computation of the correlation coefficient function, the number of searches is in most cases much smaller than N^2. We deal here only with translation, since this is the most costly part of an image registration problem, as it is pointed in [7], where the rotation and translation distortions are faced separately. Some preliminary results of this work were presented in [17].

The paper is organized as follows. In Section 2 the problem is formulated and the proposed measure along with the closed-form solution are given. In Section 3 experimental results that evaluate the performance of the proposed subpixel registration technique and compare it to other techniques are provided. The new iterative scheme and some experiments concerning its complexity are presented in Section 4. Finally, the work is concluded in Section 5.

2. Subpixel image registration

2.1. Problem formulation

Let $f(i,j)$ be a reference image and $w(i,j)$ a window in $f(i,j)$, with dimensions $n \times n$ and with its *support* defined by the set

$$\mathscr{S} = [0, n-1] \times [0, n-1]. \tag{1}$$

Let also $g(i,j)$ be a search area in a translated version of image $f(i,j)$, $f_t(i,j)$, with dimensions $m \times m$ (where $m > n$). For both $w(i,j)$ and $g(i,j)$, the upper left corner is located at the origin of a global coordinate system. Then, it is clear that all the possible positions of window $w(i,j)$ in the *search area* $g(i,j)$ take values in the following set:

$$\mathscr{A} = [0, N-1] \times [0, N-1], \quad N = m - n + 1 \tag{2}$$

and their maximum number is upper bounded by the cardinality of set $\mathscr{A}$, i.e., N^2.

Let now $s_{\mathbf{x}}(i,j)$ be a window of the search area $g(i,j)$ that has the same size with w, with $\mathbf{x} = [x, y]^t \in \mathscr{A}$, $(i,j) \in \mathscr{S}$ denoting the coordinates of its upper left corner, and the relative coordinates of the pixels of the window with respect of its upper left corner, respectively. Then, the image registration problem can be stated as a searching